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Oxyfuel combustion in the steel industry: energy efficiency and decrease of CO₂ emissions

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1. Introduction

The use of oxygen technologies within the steel industry has become increasingly important. During the last decades increased throughput capacity and lowered average cost have been the driving forces, however, today the positive impact on energy savings and reduced emissions have come into the focal point, a fact that seems to be even further pronounced in the future. This chapter describes how the oxygen technologies contribute to increased energy efficiency in the melting and heating processes, how it reduces the fuel consumption and CO₂ emission, and how in-plant generated low calorific gases can be effectively used to further improve the overall energy efficiency of a steel production plant, reduce costs and environmental impact.

The main production routes for steel are the integrated steel mill and the mini-mill. The integrated steel mill uses iron ore as main source for iron, and includes processes like ore sintering, coke-making, blast furnace iron-making and basic oxygen steel-making. The main piece of equipment at a mini-mill is the electric arc furnace where steel scrap, its main raw material, is melted. Both routes include subsequent casting and downstream heating and rolling (or forging) operations.

Dependent on production route and status, a steel mill need 700 to 4,000 kWh to produce 1 tonne of finished product. This corresponds to a CO₂ emission of about 0.35 to 2.2 tonne per tonne of steel produced. However, there are great opportunities to increase the efficiency, using oxygen technologies make a substantial positive impact. Relating to how the oxygen is introduced, we basically distinguish between injection of oxygen (normally through a lance) and oxyfuel combustion (applying a burner), however, the end result is the same: oxyfuel combustion. The main processes where oxygen technologies can be applied are: electric arc furnace for scrap melting, blast furnace iron-making, preheating of different vessels (ladles, etc.), and in the downstream reheating and heat treatment.

It is a well-known fact that only three things are needed to start and maintain combustion: oxygen, fuel, and sufficient energy for ignition. The combustion process itself would be most efficient if fuel and oxygen can meet without any restrictions. However, in practice it is not simply a question of efficient combustion, the heat transfer efficiency is also extremely important. Nevertheless, it has been clearly demonstrated that if oxygen (and not air) is

used to combust a fuel, all the heat transfer mechanisms (convection, conduction and radiation) can be promoted at the same time. Air contains 21% oxygen and 79% ballast. In a combustion process, this ballast, practically all nitrogen, has to be heated, without taking part in the process. By using oxygen instead of air we get the beneficial oxyfuel combustion. New demands and challenges from the industry have been met by a continuous development work. As a result, in parallel to the conventional oxyfuel – for example widely used to boost melting in electric arc furnaces – there are today established very interesting technologies. Among those, the most important ones seem to be flameless combustion and direct flame impingement. These new technologies not only fulfil the existing needs with astonishing results, they also open up for completely new areas of application.

Flameless oxyfuel is today applied in drying and preheating of ladles and converters, for heating in reheat furnaces and annealing lines, and for melting when avoiding oxidation. It provides excellent temperature uniformity and reduced NO_x emissions. Additionally, it can be applied in, for example, preheating of air in the blast furnace hot stoves.

The use of direct flame impingement has so far been limited to boosting of strip annealing and galvanizing lines, but its opportunities are almost uncountable. For example, there are ideas about applying this technology to substantially shorten process routes by omitting process steps, or using it in the iron-making step.

In reheating, today's best air-fuel solutions need at least 1.3 GJ (360 kWh) for heating a tonne of steel to the right temperature for rolling or forging; employing oxyfuel the comparable figure is below 1 GJ, a saving of 25%. For continuous heating operations it is also possible to economically operate the furnace at a higher temperature at the entry (loading) side of the furnace. This will even further increase the possible throughput in any furnace unit. Oxyfuel combustion allows all installation pipes and flow trains to be compact without any need for recuperative or regenerative heat recovery solutions. Combustion air-blowers and related low frequency noise problems are avoided.

Oxyfuel solutions deliver a unique combination of advantages in reheat and annealing. Thanks to improved thermal efficiency (about 80% compared with 40-60% for air-fuel), the heating rate and productivity are increased and less fuel is required to heat the product to the desired temperature, at the same time saving on CO_2 and NO_x emissions. In summary the results include:

- Throughput capacity increase of up to 50%
- Fuel savings of up to 50%
- Reduction of CO_2 emissions by up to 50%
- Reduction of NO_x emissions
- Reduction of scaling losses (improving the material yield)

Compared with conventional oxyfuel, flameless oxyfuel provides even higher production rates, excellent temperature uniformity and very low NO_x emissions. Since its commercial introduction in 2003, the leading supplier has made more than 30 installations of the flameless oxyfuel technology, some using a low calorific fuel.

This chapter describes the state-of-the-art of oxygen technologies, including results from installations in the steel industry, and discusses their future very interesting possibilities to make the steel production more effective. Oxyfuel combustion has begun to make the steel industry more energy efficiency, but more can be done and, moreover, those technologies can be employed also in other branches of the industry, there as well making improvements of 20-50%.

2. Oxyfuel combustion technologies

Oxyfuel combustion refers to the use of pure, that is industrial grade, oxygen instead of air for combustion of fossil fuels. Oxyfuel technology offers a number of advantages over air-fuel combustion. In air-fuel combustion the burner flame contains nitrogen from the combustion air. A significant amount of the fuel energy is used to heat up this nitrogen. The hot nitrogen leaves through the stack, creating energy losses. When avoiding the nitrogen ballast, by the use of industrial grade oxygen, then not only is the combustion itself more efficient but also the heat transfer. Oxyfuel combustion influences the combustion process in a number of ways. The first obvious result is the increase in thermal efficiency due to the reduced exhaust gas volume, a result that is fundamental and valid for all types of oxyfuel burners. In combustion gases, heat radiation is mainly from CO₂ and H₂O molecules. As there is no, or very low, nitrogen content in an oxyfuel furnace atmosphere, the concentration of highly radiating CO₂ and H₂O will be very high, a fact which considerably increases heat transfer by gas radiation. A striking feature of oxyfuel combustion is the very high thermal efficiency even at high flue-gas temperatures and no preheating of fuel or oxygen.



Fig. 1. An ingot for bearing steel production is lifted out of a soaking pit furnace at Ascométal in France. The furnace is fired with flameless oxyfuel, heating the ingots uniformly to over 1200°C.

In addition to using a burner for the combustion, which normally is operated at stoichiometric conditions, two other technologies should be mentioned: lancing, and post-combustion. Lancing refers to injecting oxygen, sometimes at very high velocities into furnace free-space or a melt. It is done to intensify the air-fuel combustion, either to combust for example carbon into CO, or achieve a complete combustion of a fuel into products like CO₂ and H₂O. Typically it is employed an Electric Arc Furnace (EAF) for scrap melting, but it could also be like in the case of the REBOX® HLL technology to improve reheating.

Post-combustion does in most cases in this context refer to the reaction $\text{CO} + \frac{1}{2}\text{O}_2 = \text{CO}_2$, which is strongly exothermic; the released energy is typically used to improve melting. Generally speaking, the prerequisites for a beneficial post-combustion are CO generation,

oxygen available, and a high heat transfer. For example, charging coal with the scrap in an EAF so that it dissolves into the hot heel and blowing oxygen into the hot heel at simultaneous over-stoichiometric operation of the oxyfuel burners when there is scrap in the furnace, provides such wanted conditions. Post-combustion at flat bath operation, on the other hand, normally provides too low heat transfer efficiency.

2.1. Flameless oxyfuel combustion

Some very interesting technologies have emerged in parallel with conventional oxyfuel, which is widely used to boost melting in electric arc furnaces. The most important ones are flameless combustion and Direct Flame Impingement (DFI). These new technologies not only fulfil existing needs with astonishing results, they also open up completely new areas of application. The flameless combustion creates a huge practically invisible oxyfuel flame whereas the DFI technology uses small, well-defined sharp flames.

Increasingly stricter legislation on emissions led to the development of flameless oxyfuel, which was introduced for the first time in 2003 in continuous furnaces for strip annealing and slabs reheating, both at the stainless steel producer Outokumpu. The expression 'flameless combustion' communicates the visual aspect of the combustion type, that is, the flame is no longer seen or easily detected by the human eye. Another description might be that combustion is 'extended' in time and space – it is spread out in large volumes, and this is why it is sometimes referred to as 'volume combustion'. Such a flame has a uniform and lower temperature, yet containing same amount of energy.

In flameless oxyfuel the mixture of fuel and oxidant reacts uniformly through flame volume, with the rate controlled by partial pressures of reactants and their temperature. The flameless oxyfuel burners effectively disperse the combustion gases throughout the furnace, ensuring more effective and uniform heating of the material even with a limited number of burners installed. The lower flame temperature is substantially reducing the NO_x formation. Low NO_x emission is also important from a global warming perspective; NO_2 has a so-called Global Warming Potential that is almost 300 times that of CO_2 .

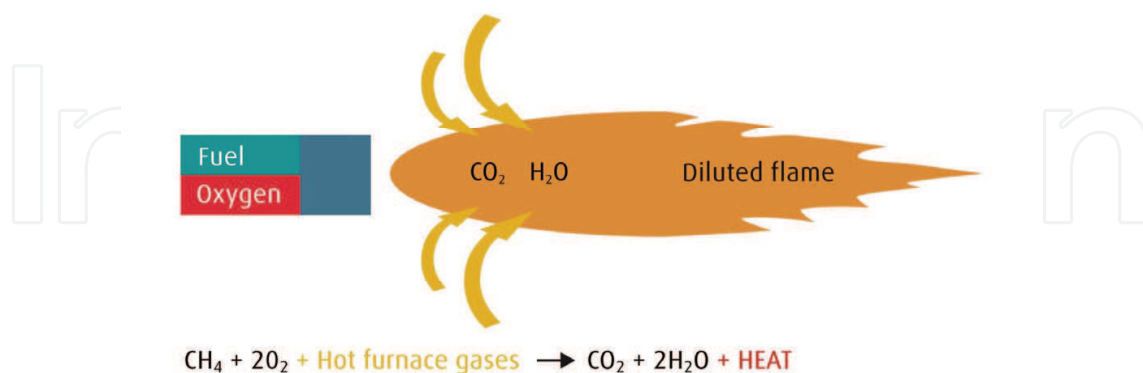


Fig. 2. The principle way of creating flameless combustion; the flame is diluted by the hot furnace gases. This reduces the flame temperature to avoid creation of thermal NO_x and to achieve a more homogenous heating of the steel.

Compared with conventional oxyfuel, flameless oxyfuel provides even higher production rates, excellent temperature uniformity and very low NO_x emissions. The first installations of this innovative flameless oxyfuel technology were made by Linde. Since 2003 over 30 installations of this technology have been made at more than a dozen sites, some even using a low calorific fuel. There seems to be an increasing need to combust low calorific fuels; for fuels containing below 2 kWh/m^3 , use of oxygen is an absolute requirement for flame temperature and stability. At integrated steel mills use of blast furnace top gas ($<1 \text{ kWh/m}^3$), alone or in combination with other external or internal fuels, is becoming increasingly important. Flameless oxyfuel can be successfully employed here. The first installations of flameless oxyfuel took place in reheating and annealing, but it was quickly adopted also for preheating of ladles and converters. The next area to be exploited, with substantial positive impact, is the blast furnace hot stoves.

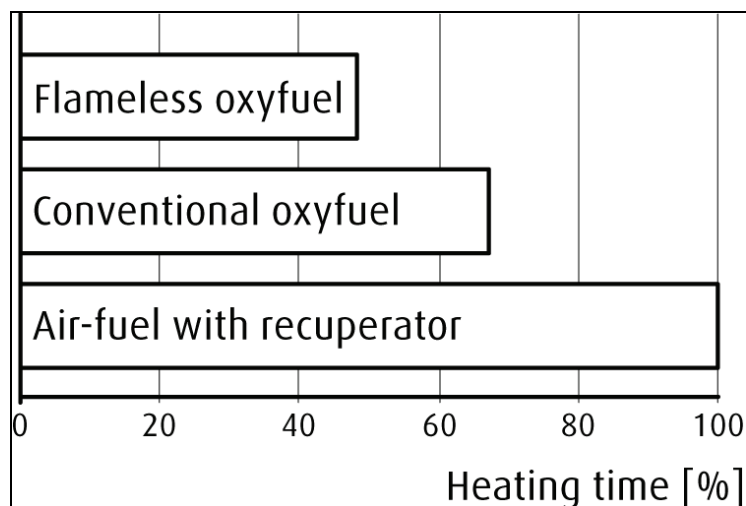


Fig. 3. A comparison of the results from installations at Ovako's Hofors Works, Sweden using different combustion technologies. When conventional oxyfuel was installed the heating time decreased by 30%, but with flameless oxyfuel it was possible to run a heating time half of the original one with air-fuel. It should be noted that the power has not been increased, but decreased.

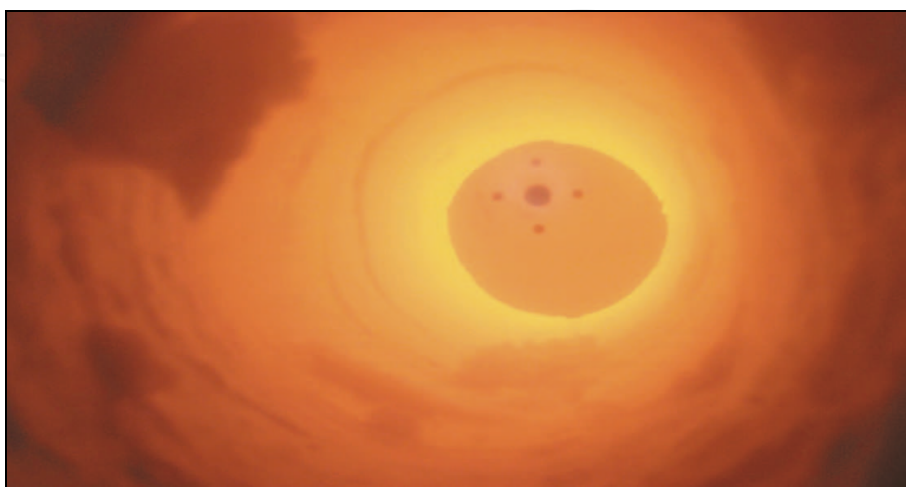


Fig. 4. A flameless oxyfuel flame; the flame is diluted and almost transparent. The combustion in this photograph is using a low calorific fuel.

2.2. Direct Flame Impingement

It is also possible to fire with oxyfuel flames directly onto a material. This is what we call DFI, Direct Flame Impingement. DFI Oxyfuel is a fascinating compact high heat transfer technology, which since 2002 provides enhanced operation in strip processing lines, for example at galvanizing. It is patented by Linde. So far the use of DFI Oxyfuel has been to boost strip annealing and hot dip metal coating lines. Use of DFI Oxyfuel reduces the specific fuel consumption while delivering a powerful 30% capacity increase, or more. Installations are found at Outokumpu's Nyby Works in Sweden and ThyssenKrupp at Fintentrop and Bruckhausen in Germany. The latest installation is in a continuous annealing line at POSCO in Pohang, South Korea. Due to DFI's effective pre-cleaning properties there are also benefits relating to surface appearance and improved adhesion of metal coatings.

The main benefits of DFI Oxyfuel are:

- Significantly higher heat transfer resulting in increased production capacity
- Lower fuel consumption
- Ability to use high power input in limited furnace volume
- Compact and powerful unit for easy retrofit
- Heating and cleaning in one operation
- Option to modify surface conditions

Tests have verified the higher level of local heat flux for the DFI Oxyfuel technology. In general, the use of oxyfuel combustion substantially increases the thermal efficiency of a furnace. This is primarily due to the fact that radiant heat transfer of furnace gases produced by oxyfuel combustion is significantly more efficient than those of air-fuel. Due to the absence of nitrogen in the combustion mixture, which does not need to be heated, the volume of exhaust gas is also substantially reduced, thus lowering total heat loss through the exhaust gas. Thanks to improved thermal efficiency, the heating rate and productivity are increased and less fuel is required to heat the product to a given temperature, while at the same time economizing on fuel and reducing CO₂ emissions.

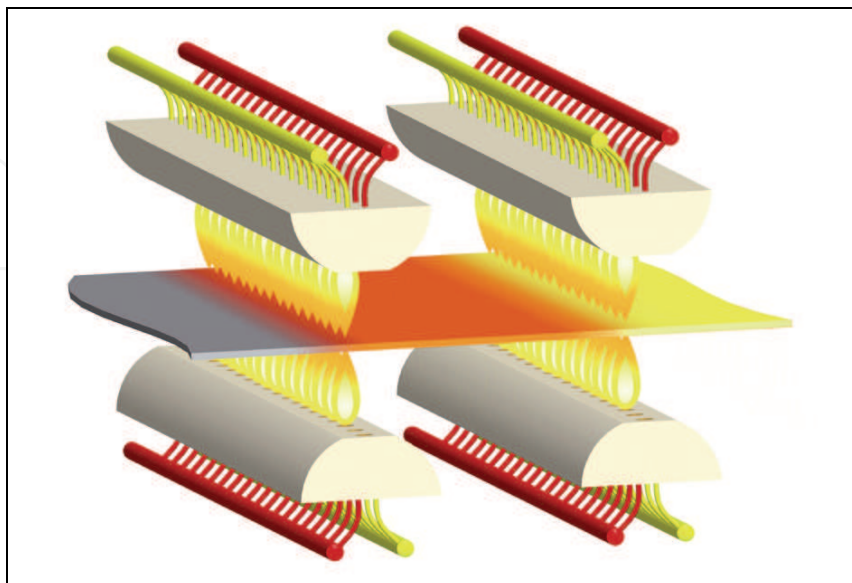


Fig. 5. The principle of DFI with many small oxyfuel flames heating directly onto the material.

The DFI unit has a thermal efficiency of around 80%. This reduces the specific fuel consumption while delivering a powerful 30% capacity increase in an existing strip processing line. In galvanizing, zinc adhesion and surface appearance are also improved due to DFI's effective pre-cleaning properties, leaving both strip and furnace rolls cleaner than before.

It is important to note that applying a DFI Oxyfuel system for preheating a strip does not create an oxidation problem; for example, experience with preheating up to 300°C shows no problems. In metal coating lines, the thin oxide layer formed is reduced in the subsequent reduction zone. It is also possible to influence the oxidation level to a certain extent by adjusting the stoichiometry of the flames.

3. At the integrated iron and steel processes

To produce iron in solid or liquid form from iron ore a reductant is needed. The two most suitable reductants, from a technical and economic perspective, are carbon and hydrogen. The use of pure hydrogen is today frequently not realistic; there are a few exceptions but these are linked to unusual localised conditions. In practice, the reductants used in today's iron-making are coal and natural gas; the coal being in the form of coke or pulverized coal. Blast furnaces inevitably require coke to a certain extent. It should be noted that the lowest operational limit of coke in a shaft furnace has been estimated at 150-200 kg/t. This is determined by the requirements for the carburization of iron, direct reduction with carbon and, in particular, shaft permeability and burden support.

To improve throughput and decrease of CO₂ emissions, so-called Full Oxygen Blast Furnace processes are frequently discussed as a possible alternative. The idea of the Full Oxygen Blast Furnace (FOBF) is not new; some researchers discussed it back in the 1930s and 1950s. The modern ideas were presented in the 1980s. They are based on two main principles: using pure oxygen as blast instead of air to create oxyfuel combustion of the injected pulverized coal, and acquiring a pre-reduction degree of iron (for example, 90%). However, FOBF processes are hampered by the so-called "hot bottom and cold top problem". Since Fink presented a proposal for an FOBF process in a patent in 1978, the idea of using recirculated top gas for compensating the decreasing amount of shaft gas and adjusting the very high flame temperature has been the basis for most other proposals.

Lately, FOBF processes – which have not yet been taken into full-scale operation – have experienced a renaissance, seen by many as the best way to decrease CO₂ emissions. The potential benefit of FOBF processes lies in the possibility of achieving a top gas with low nitrogen content (with a calorific value of 2 kWh/Nm³, more than twice that of conventional blast furnaces) from which the CO₂ can then be removed reasonably effectively. The top gas is then recirculated back into the furnace as part of the fuel input. The captured CO₂ can be disposed of so that it is not discharged into the atmosphere or, for example, used in oil and natural gas fields. Using FOBF processes is a possible solution, but it is not yet a proven alternative.

Large benefits can be achieved from improved utilization of gases from other facilities on site, like coke oven gas from the coke-making and BOF gas from the steel-making converter (Basic Oxygen Furnaces – BOF). As the energy content of those gases are rather low, from half that of natural gas and downwards, combustion with oxygen is very beneficial or even

necessary. This could take place when injecting into the blast furnace or when using them as fuel in different types of heating operations. This also applies to use of blast furnace top gas.



Fig. 6. Blast furnace hot stoves, the large heat exchangers for heating the air-blast to over 1000°C prior to injection into the blast furnace tuyères.

An area where increased use of blast furnace top gas could be very beneficial is at the hot stoves. Use of flameless oxyfuel in blast furnace hot stoves is now under way. An evaluation of applying the technology in a large modern and efficient blast furnace, which produces a low calorific top gas, includes the following key observations:

- 25% of flue-gas can be recycled and this leads to a modified flue-gas composition containing 60% CO₂, accordingly increasingly suitable for Carbon Capture and Sequestration.
- The heat transfer by radiation is increased by 15% relative to conventional practices and this will manifest as improved stove efficiency.
- 60% of the fuel gas enrichment can be eliminated.
- The total energy use at the hot stove is reduced by 5%.
- The temperature of the blast increases by about 15°C.

Use of flameless oxyfuel in blast furnace hot stoves could, thus, replace combustion of coke oven gas or natural gas in this process with blast furnace top gas. This would typically cover the cost for the oxygen, or even provide a minor cost saving. The coke savings arising from an increase blast temperature will be substantial. In addition to the energy and environmental benefits, the stoves campaign life will be increased.

4. At the electric arc furnace

Today's electric arc furnace (EAF) for producing steel from scrap can be considered as a very sophisticated piece of equipment. During the 20th century, the development of electric steelmaking has been tremendous. In 1910, the electric furnaces, including both EAFs and induction furnaces, produced 0.2% of the world steel production, today this figure is nearly 35%. The two main factors explaining this evolution are the increased scrap availability and the development of ladle metallurgy, especially with the introduction of the ladle furnace (ASEA-SKF in 1965), which made it possible to increase both the production rate and the product quality. We should also bare in mind the favour of a much lower capital requirement as compared with the integrated steel mills.

When operating a modern EAF, the energy turnover is about 650 kWh/t, but only 60% of that energy is needed to heat and melt the scrap. A decrease of the energy turnover as such can be a goal, but many EAF mills consider a decrease of the electricity consumption as a more important way to cut costs and to enable an increased production rate. Decreased electricity consumption also offers additional advantages, such as lowered costs for electrodes and less disturbances on the grid. Moreover, electricity prices are at many places increasing. The electricity consumption can be lowered either by decreasing the total energy turnover or by replacing the electricity with energy in another form. It should be noted, that the electrical transmission losses are a direct function of the electricity consumption, representing >6% of the electricity supplied in an AC furnace and even more in a DC furnace.

The increasing use of oxygen has been very important for the development of EAF steelmaking. It begun with the (manual) oxygen lancing, in a first step used to replace the iron ore added during the refining period, but via oxyfuel burners and post-combustion it has developed into a number of more and more sophisticated applications. Today there are EAFs with a specific oxygen use above 50 Nm³/t, more than the Basic Oxygen Furnace (BOF) in integrated steel mills.

The average ratio between the electricity savings and the oxygen use, should be about 3.5 kWh/Nm³ O₂. When introducing oxygen into an EAF, oxyfuel burners and oxygen lancing are employed in a first stage up to a total use of some 20 to 25 Nm³/t usually with savings in electricity of about 5 kWh/Nm³ O₂ or more and with a corresponding increase of the production rate. When evaluating the overall reaction for oxygen lancing, ($C + \frac{1}{2}O_2 = CO$), one should expect electricity savings to be maximum about 2 kWh/Nm³ O₂ even taking into account the higher contribution from dissolved carbon in steel scrap and adding energy corresponding to a possible post-combustion value of 8% in the bath-slag system. However, the much higher savings actually achieved, can be explained as follows. The overall reaction takes place in two steps: (1) the injected oxygen immediately combines with iron to form iron oxide, a strongly exothermic reaction, and (2) iron oxide in the slag is reduced by carbon, an endothermic reaction. The first reaction releases almost four times more heat per Nm³ O₂ than the overall reaction and this heat will be absorbed by surrounding scrap and significantly speed up the melt-down process.

Operating an EAF with under-pressure and especially with the slag door open during most of the operation leads to a heavy in-leakage of air. The oxygen part of this air could of course be of use inside the furnace, but the nitrogen (and argon) part is only to be considered as ballast. The energy demand for heating-up the ballast nitrogen, due to in-leakage of air, is 50-60 kWh/t. Even much higher figures, above 100 kWh/t, have been found at several EAF shops. The solution to this is to keep the slag door shut during the main part of the operation and run the furnace with a slight overpressure.

Since oxygen lancing was introduced, it has at most EAF shops been carried out by lancing through the slag door. Even if this way of lancing allows moving the injection point in all directions, the oxygen introduced will not be equally distributed throughout the bath. The trend of the EAF becoming more and more air-tight and the dynamic impact of a shorter meltdown time made it increasingly harder to use the conventional way of lancing oxygen and coal through the slag door. Nowadays we find combined equipment including all the functions: oxygen lancing, coal lancing, oxyfuel burners, and post-combustion. This equipment can be considered as combined lance-burners often with a coherent jet function

enabling high-velocity injection, with a device for coal injection, where the burner also can be run overstoichiometrically to provide post-combustion or there is a separate nozzle for oxygen injection. To secure a good distribution of the heat supply throughout the furnace, including also the rear end of an Eccentric Bottom Tapping (EBT) type furnace, and the advantage of combining oxygen injection with oxyfuel burner operation, we end up with a minimum of four wall-mounted injection devices (assuming an AC furnace) – one at each cold spot between the electrodes and one in the EBT area.

The main factor limiting the energy supply from oxyfuel burners in an EAF is the heat transfer efficiency, which decreases with increased scrap temperature - we here have to compare with heat transfer from the electric arcs. However, as long as this heat transfer efficiency enables a decreased average cost for the production, it is of course beneficial to run the oxyfuel burners. Generally speaking, this normally means operation of the oxyfuel burners during about half of the time needed for the melting of each bucket of scrap charged, but the time is also a function of the production rate demand.

The CO/CO₂ ratio in equilibrium with liquid steel is high, even at low carbon contents. This result in a CO-rich gas leaving the bath-slag system in the furnace providing a potential for large energy recovery if this CO can be burnt with O₂ into CO₂ and the heat released be transferred to the metal. To illustrate the potential of post-combustion, we can say that in an EAF operation with a high coal injection, the energy released from the formation of CO is about 25 kWh/t, but if this entire CO can be transferred into CO₂ the total amount of energy released will be about 140 kWh/t. This should preferably be done with pure oxygen in order to minimize losses to the flue-gases.

Electricity savings from post-combustion are in the range 3-5 kWh/Nm³ O₂, and can be obtained with rather simple means such as oxygen injection at fixed flow rates through existing oxyfuel burners during fixed periods of time, or by running the oxyfuel burners overstoichiometrically. For reaching high values, oxygen flow control through on-line flue-gas analysis and separate post-combustion lances can be used, making a heat recovery of 60-75% reasonable.

5. At vessel preheating

The use of oxyfuel to preheat vessels such as torpedoes, ladles and converters has been around for several decades. However, the number of installations is still surprisingly low given its potential. Using oxyfuel instead of air-fuel would reduce the fuel consumption drastically by approximately 50%, which would bring about a proportional decrease in CO₂ emissions. However, it would also have additional benefits such as a shorter heating time and hotter vessels. These would, for example, lead to fewer ladles in circulation and the possibility of reducing tapping temperatures. The latter directly saves energy in the furnace, but it could also decrease the tap-to-tap time of the furnace. The time saving would lead to additional energy savings as the specific (time dependent) heat losses from a furnace, would then be lowered.

If an oxyfuel ladle preheating system is installed adjacent to the EAF, preferably just a few metres away from the tapping position, very hot ladles can be used. Experience shows that such a measure would allow 20 minutes decreased ladle cycle and a 15°C lowered EAF tapping temperature, providing electricity savings at 5-6 kWh/t.

Let us look at a proven example of what this could lead to. The operating power with oxyfuel for a 60t ladle is approximately 1.2 MW. The average annual level is 0.8 MW, which at 7,500 h/y means 6 GWh/y. This is around half of what would be required with air-fuel; thus the annual saving is 6 GWh. Assuming the fuel is natural gas, the resulting decrease in CO₂ emissions would be 1,200 t/y, and this is only for one preheating station; normally there are multiple at each site.



Fig. 7. Ladle preheating using flameless oxyfuel at Ovako's Hofors Works, Sweden.

Conventional oxyfuel delivers a simple, compact and low weight installation as compared to an air-fuel system with a recuperator or regenerative solution. However, in preheating of vessels flameless oxyfuel brings additional strong advantages. Flameless oxyfuel is seen as the best available technology for heating and not only allows for ultra low NO_x emissions, but brings extended refractory life through more uniform temperature distribution. The first installation took place in 2003. Today more than 15 installations of flameless oxyfuel are in operation, two recent cases are found at Outokumpu at Tornio, Finland and SKF at Katrineholm, Sweden.

In 2008 flameless oxyfuel preheating was installed at Outokumpu's 90 tonnes ferrochrome converter. The 2.5 MW flameless oxyfuel system is used for drying and preheating of the converter, and provides the Tornio Works with greater energy efficiency, lower fuel consumption, and reduced emissions CO₂ and NO_x.

At SKF a similar type of flameless oxyfuel technology was installed last year, but for preheating ladles. And the size is here completely different; the ladles are for just 1 tonne of steel. Six ladle preheating stands were equipped with OXYGON® flameless oxyfuel preheating systems. This installation shows that a new energy saving and environmentally friendly technology also can be viable in a smaller scale production.

6. At reheating

Prompted by rapidly rising fuel prices in the 1970s, the steel industry began to consider methods to reduce fuel consumption in reheating and annealing. This laid the foundation for the use of oxyfuel solutions in rolling mills and forge shops. In the mid 1980s, some of

these furnaces got equipped with oxygen-enrichment systems, which increased the oxygen content of the combustion air to 23-24%. The results were encouraging: fuel consumption was reduced and the output, in terms of tons per hour, increased.

Oxyfuel solutions deliver a unique combination of advantages in reheat and annealing. Thanks to improved thermal efficiency (about 80% compared with 40-60% for air-fuel), the heating rate and productivity are increased and less fuel is required to heat the product to the desired temperature, at the same time saving on CO₂ and NO_x emissions. In summary the results include:

- Throughput capacity increase of up to 50%
- Fuel savings of up to 50%
- Reduction of CO₂ emissions by up to 50%
- Reduction of NO_x emissions
- Reduction of scaling losses

In 1990, Linde converted the first steel reheating furnace in the world to operate with 100% oxygen at Timken in the USA. Since then, Linde has been pioneering the use of oxyfuel for this application. Today there are 120 reheat furnaces and annealing lines using Linde's oxyfuel solutions. The best air-fuel solutions need at least 1.3 GJ for heating a tonne of steel to the right temperature for rolling or forging. When using the REBOX oxyfuel solutions the comparable figure is below 1 GJ, a saving of 25%. For continuous heating operations it is also possible to economically operate the furnace at a higher temperature at the entry side of the furnace. This will even further increase the possible throughput in any furnace unit. Oxyfuel combustion allows all installation pipes and flow trains to be compact without any need for recuperative or regenerative heat recovery solutions. Combustion air-blowers and related low frequency noise problems are avoided.

		Air-fuel	Air-fuel with recuperator	REBOX® oxyfuel
Enthalpy in steel	kWh/t	200	200	200
Transmission losses	kWh/t	10	10	10
Flue-gas enthalpy	kWh/t	290	155*	50
Flue-gas temperature	°C	1,200	850	1,200
Air preheating	°C	20	450	20
Thermal efficiency	%	42	60	80
Energy need	kWh/t	500	365	260
Energy need	GJ/t	1.8	1.33	0.94
Oxygen production	kWh/t			25

*after recuperation

Table 1. With oxyfuel it is possible to achieve an 80% thermal efficiency, as compared with 60% in the best air-fuel cases. Even if also adding the energy needed to produce the required oxygen, we would reach 285 kWh/tonne, thus still close to 1 GJ, a saving of 20%.

During the last years flameless oxyfuel have been employed, for example in Brazil, China, France, Sweden, and the USA. Here follows some examples from those installations.

Soaking pit furnaces at Ascométal

There are flameless oxyfuel installations at two sites belonging to the bearing steel producer Ascométal in France, which is part of the Severstal Group. At Fos-sur-Mer, a turnkey delivery in 2005-2007 converted nine soaking pit furnaces into all flameless oxyfuel. The delivery included a combustion system with flameless burners, furnace upgrade, new flue-gas system, flow train, and a control system. The furnace sizes are 80 to 120 tonne heating capacity each. The results include 50% more heating capacity, 40% fuel savings, NO_x emission reduced by 40%, and scale formation reduced with 3 tonne per 1,000 tonne heated. In a second and similar project in France in 2007-2008, four soaking pit furnaces at the Les Dunes plant were also converted into all flameless oxyfuel operation.

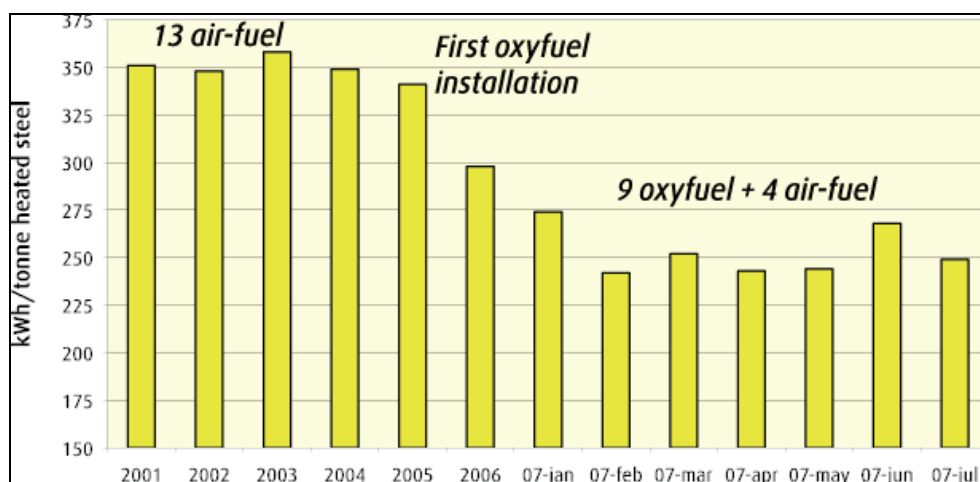


Fig. 8. Total average fuel consumption in the 13 soaking pit furnaces at Ascométal, Fos-sur-Mer. 2001-2004 was all air-fuel combustion. The first conversion into oxyfuel took place in 2005. In 2007 nine out of 13 furnaces were operated with all oxyfuel. The average fuel consumption per tonne for all furnaces was reduced by 100 kWh or 10 Nm³ of natural gas.

15 installations at Outokumpu

At Outokumpu's sites in Sweden there are a total of 15 installations. In 2003, a walking beam furnace in Degerfors was rebuilt and refurbished in a Linde turnkey project with performance guarantees. It entailed replacing the air-fuel system, including recuperator, with flameless oxyfuel, and installation of essential control systems. The resultant 40-50% increase in heating capacity provided increased loading of the rolling mill, reduction of over 25% in fuel consumption and NO_x emissions below 70 mg/MJ.

At the Nyby plant, there are two catenary furnaces, originally installed in 1955 and 1960 respectively. The catenary furnace on the first annealing-pickling line, for hot or cold rolled strips, was converted to all oxyfuel operation in 2003. Requirements for increased production combined with stricter requirements for low NO_x emissions led to this decision. The furnace, 18 m long, was equipped with flameless oxyfuel burners. The total power input, 16 MW, was not altered when converting from air-fuel to oxyfuel, but with oxyfuel the heat transfer efficiency increased from 46% to 76%. The replacement of the air-fuel system, combustion blowers and recuperators resulted in a 50% increase in heating capacity

without any increase in the length of the furnace, a 40% reduction in specific fuel consumption and NO_x levels below the guaranteed level of 70 mg/MJ.

At Avesta we find the world's largest oxyfuel fired furnace, 40 MW. The old 24 m catenary furnace had a 75 tph capacity, but the requirement was to double this whilst at same time meeting strict requirements for emissions. The refurbishment included a 10 m extension, yet production capacity was increased to 150 tph. The conversion involved the removal of air-fuel burners and recuperators and the installation of all oxyfuel. The oxyfuel technology used involved staged combustion. The conversion reduced fuel consumption by 40%, and NO_x levels are below 65 mg/MJ. This furnace is an example of another route to flameless; having been converted from conventional oxyfuel to flameless oxyfuel last year and resulting in an additional 50% reduction of the NO_x levels.

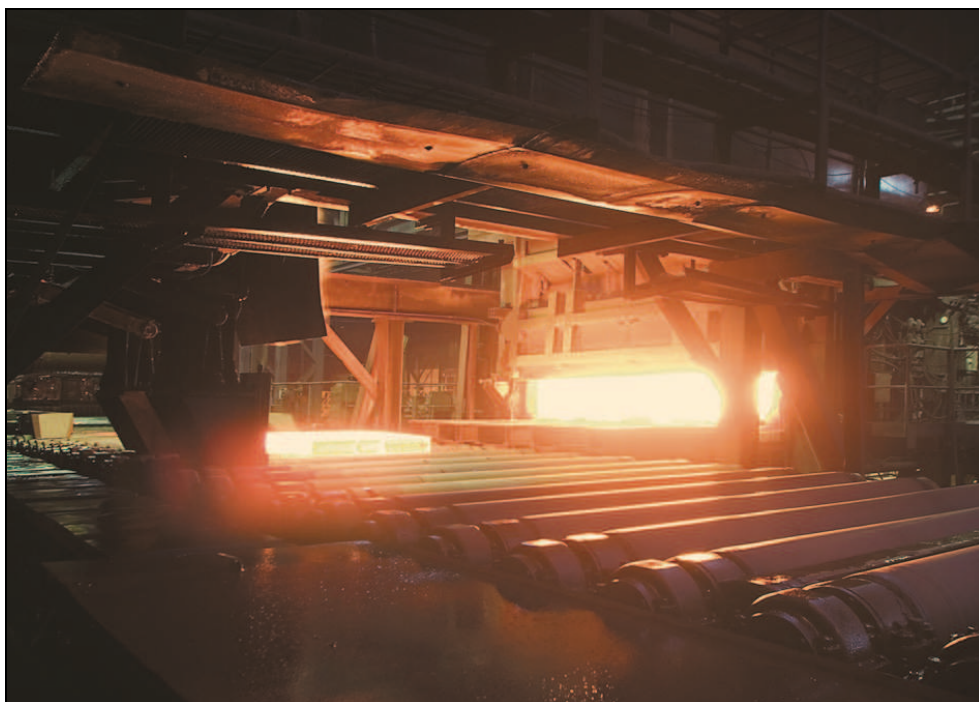


Fig. 9. A heated slab is discharged from the walking beam furnace at Outokumpu's Degerfors Works. Here flameless oxyfuel has increased the heating capacity by 40-50%.

50% fuel savings at ArcelorMittal

There have been several successful installations in rotary hearth furnaces. One is found at ArcelorMittal Shelby in Ohio, USA. In 2007, Linde delivered a turnkey conversion of a 15-metre diameter rotary hearth furnace at this seamless tube producer. It included combustion system with flameless burners, furnace upgrade, new flue-gas system, flow train, and a control system. The former air-fuel fired furnace was converted in two steps, first using oxygen-enrichment for a period of time and then implementation of the flameless oxyfuel operation. Excellent results have been achieved, meeting all performance guarantees. These included >25% more throughput, 50% fuel savings compared with oxygen-enrichment (60% below the prior air-fuel performance), CO_2 emissions dropped accordingly, NO_x emission <70 mg/MJ corresponding to 92% less on an annual basis, and 50% reduced scale formation.

In January 2010, ArcelorMittal's received the Association for Iron & Steel Technology's Energy Achievement Award for its efforts to reduce fuel consumption and emissions using the REBOX oxyfuel technical solution at its Shelby mill.



Fig. 10. Outside view of the rotary hearth furnace at ArcelorMittal Shelby after the conversion into all flameless oxyfuel operation. Please note that all bulky equipment and piping relating to the previously used air-fuel system have been removed as it no longer is of any use.

SSAB Walking Beam Furnace with REBOX HLL

At SSAB in Sweden REBOX HLL is used. The slabs are reheated in walking beam furnaces with a capacity of 300 tph per furnace, from ambient temperature to 1,230°C. The air-fuel combustion system uses a recuperation system to preheat air to 400°C. The fuel is oil, and prior to the HLL installation the consumption was 440 kWh/tonne, or 1.58 GJ/tonne.

REBOX HLL creates a type of flameless oxyfuel without replacing the existing air-fuel burners. By reducing the air flow and substituting high velocity oxygen injection into the combustion, great benefits can be achieved. 75% of the oxygen needed for the combustion is supplied with this technique. The flue-gas volume is less than 45% that of air-fuel. The system start-up took just one day. The installation in only one zone has increased the heating capacity from 300 to 320 tph.

The installation of HLL is rather easy because it does not include any replacement of burners or installation of additional burners, which minimizes the installation down time. The air-fuel system can at any time be brought back into operation as it was before. This eliminates any potential risk relating to the implementation, and it enables operation to be flexible and optimized in response to fluctuating fuel cost and production requirements.

Some important results from this installation are:

- No negative impact on the surface quality.
- A positive impact on the temperature uniformity of the slabs.
- The ideal heating curve suggested by the control system can be achieved more easily.
- Less smoke emanating from the furnace, greatly improving the plant environment.

Based on the results of current installation in one zone, SSAB has estimated that a full implementation would provide the following:

- A reduction of NO_x emission by 45%.
- Fuel consumption can be decreased by 25%, leading to the same reductions in SO₂ and CO₂ emissions.
- Production throughput can be increased by 15-20%.

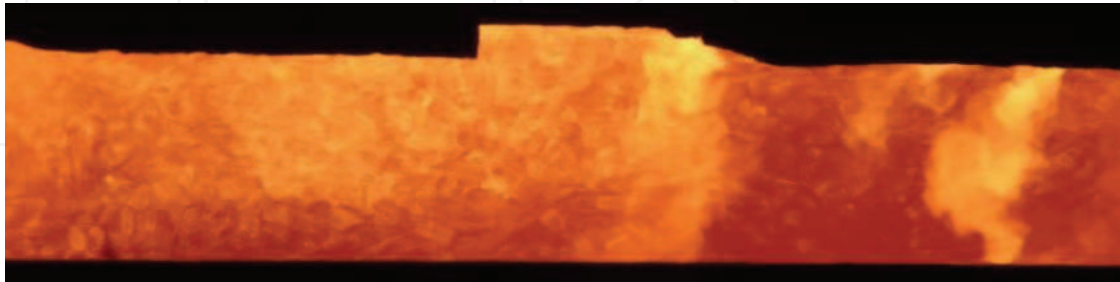


Fig. 11. "Semi-flameless" oxyfuel combustion in a 300 tph walking beam furnace at SSAB, Sweden.

Stainless wire annealing in China

At Dongbei Special Steel Group in China, a new state-of-the-art annealing furnace for stainless steel wire has been taken into operation in 2010. It applies a combined technology called REBOX DST (Direct Solution Treatment), the benefits compared with a conventional solution are extremely huge, for example the treatment time is drastically reduced. The flameless combustion here uses a low calorific fuel with an energy content of 1.75 kWh/Nm³ (6.3 MJ/Nm³).

7. At strip processing

Flameless oxyfuel can be used for heating at strip processing, but the real difference here is made by applying DFI Oxyfuel, a fascinating, compact, high-heat transfer technology, which provides enhanced operation in strip processing lines such as galvanizing. DFI Oxyfuel has been used to boost capacity of strip annealing and hot dip metal coating lines by 30% or more, while reducing the specific fuel consumption. Systems are in operation at Outokumpu's Nyby Works in Sweden and ThyssenKrupp's works at Fintentrop and Bruckhausen in Germany. In mid 2010 a unit was installed in a continuous annealing line at POSCO in Pohang, South Korea.

Since the beginning of the 1990s, Linde has pioneered the use of 100% oxyfuel applications in reheat furnaces in close cooperation with customers such as Outokumpu. At Outokumpu's Nyby site in Sweden, the company wanted to increase the production capacity of a stainless strip annealing line, but the furnace already contained an oxyfuel combustion system and had extremely limited physical space available. In 2002, the first compact DFI Oxyfuel unit was installed, making it possible to increase the production by 50% (from 23 to 35 tph) without extending the furnace length. This DFI Oxyfuel installation consisted of a 2-metre long DFI unit at the entry side with four burner row units including a total of 4 MW installed power distributed on 120 oxyfuel flames.

In 2007, the REBOX DFI system was installed at ThyssenKrupp Steel's (TKS) galvanizing and aluminizing line in Bruckhausen, Germany. Earlier, Linde had installed a DFI unit at

the TKS galvanizing line at Finntrop, and increased production from 82 to 105 tph, or over 30%. The results at the Bruckhausen installation matched those in Finntrop: increasing capacity from 70 to 90 tph. Oxyfuel not only effectively heats – contributing to a reduction of fuel consumption – but also cleans, thus eliminating the need for the pre-cleaning section. In addition, the process made it possible for ThyssenKrupp to pre-oxidize steel strips in a precise and controlled manner. Prior to the DFI installation, the Finntrop plant had a 25 m long pre-cleaning section with electrolytic cleaning and brushes.

At Finntrop, to minimize line downtime, the design resulted in a 3-metre long DFI unit equipped with four burner row units, with a total of 120 oxyfuel flames and 5 MW installed power, with an option of two more row sets for an additional 2.5 MW. Three metres of the existing recuperative entry section was removed to fit the DFI Oxyfuel unit. The number of burner row units and burners employed depend on set preheating temperatures and the actual strip width and tonnage. At 105 tph, DFI Oxyfuel results in an immediate steel strip surface temperature increase of more than 200°C.

With the DFI unit the capacity of the Finntrop line increased from 82 to 109 tph. The DFI Oxyfuel unit also manages to burn off residue, particles, grease and oil from the strip rolling process, providing a cleaner strip than the long electrolytic and brush strip pre-cleaning section used to do. At a production level of 36,000 tonnes per month at Finntrop, results include an over 5% reduction in natural gas consumption, almost 20% less NO_x emissions, and a reduction of 1200 tonnes per year in CO₂ emissions.

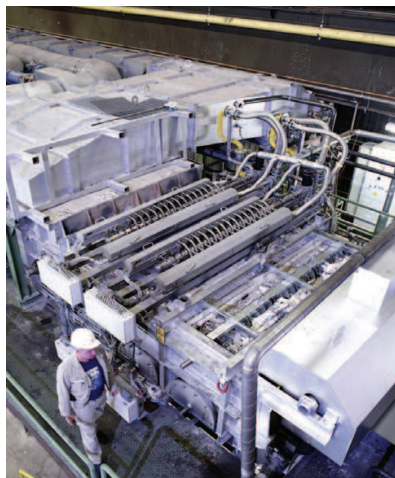


Fig. 12. REBOX DFI installation in a galvanizing line at ThyssenKrupp Steel at Finntrop, Germany. The 3-metre long DFI unit was fitted into the previous (non-fired) dark-zone.

The oxidation is lower than normal at a specific strip temperature since the dwell time is very limited; applying DFI Oxyfuel for preheating a strip up to 300°C does not create oxidation problems. In metal coating lines, the thin oxide layer formed is reduced in the subsequent reduction zone. It is also possible to influence the oxidation by adjusting the stoichiometry of the flames, for example by changing the lambda value from 1.0 to 0.9.

The oxide layer thicknesses have been measured to be in the range of 50-100 nanometres, even at high strip temperatures. A well performing reduction zone should be able to reduce the scaling further. For high strength steel, a small formed oxide layer, for instance, 200 nm, may be beneficial, since after reduction in the Radiant Tube Furnace section, pure iron will form on the surface for improve zinc adhesion.

Cleaning tests show that the carbon and iron fines contaminations can be drastically reduced by use of DFI. With the DFI Oxyfuel technology the cleaning section can be shortened to a spray cleaning section, one brush machine and a final rinsing section. The final cleaning operation is transferred to the DFI Oxyfuel inside the thermal section. The elimination of one brush machine and the electrolytic cleaning section brings considerable cost savings in maintenance and operation due to energy savings and less wear parts. Furthermore, DFI gives potential to reduce investment and operating costs in the furnace section since the furnace length can be reduced; the preheating and one heating zone can be saved.

This year, 2010, REBOX DFI is for the first time employed in a continuous annealing line for carbon steel, at POSCO's large integrated steel mill at Pohang, South Korea. The DFI unit provides a guaranteed level of preheating which will be capable of achieving approximately 15% higher capacity in the annealing furnace. The natural gas fired DFI unit consists of four oxyfuel burner row units with a combined capacity of close to 6 MW.

8. Opportunities for decreasing CO₂ emissions

There is a strong political will to decrease CO₂ emission. The steel industry only accounts for some 3% of worldwide CO₂ emissions, which totals roughly 30 billion tonnes per annum relating to the human activity of burning of fossil fuels, but seems to be strongly affected by this. To radically change existing processes and production routes to decrease the CO₂ emissions would be extremely expensive, even if it were possible.

However, there exist today a number of proven solutions and technologies which, if fully implemented, could substantially decrease CO₂ emissions without seriously altering current methods of operation and are therefore short-term viable solutions. If these solutions are fully implemented, the combined impact on CO₂ emissions from the steel industry worldwide is estimated to be a reduction of 100 million tonnes of CO₂ per annum within a relatively short time span. Among these solutions, the most viable is oxyfuel combustion.



Fig. 13. A look through the furnace door of the rotary hearth furnace at ArcelorMittal Shelby, USA; a flameless oxyfuel burner is firing straight towards the open door. Here the conversion from air-fuel to flameless oxyfuel led to a 60% reduction of the CO₂ emission.

CO₂ emissions from the steel industry have two main sources: reduction processes, and melting and heating processes. It is well known that reduction processes are the dominant

source. The two main routes for steel production account for quite different impacts on CO₂ emissions: integrated steel mills, including all upstream processes, average approximately 2 tonnes of CO₂ per tonne of hot rolled plate; for mini-mills, the corresponding figure is 0.5-0.6 tonnes. However, the contribution from heating processes is not negligible; each piece of steel is on average heated twice on its journey through the production chain, and this is far from the only heating process. Accordingly, by increasing the energy efficiency in the heating processes, a large impact can be made on reducing the carbon footprint. An additional advantage is the low flue-gas volumes with high concentration of CO₂, which enable directing it to capturing and potentially sequestration.

Use of a fuel with a low calorific value is of interest in this context. It could, for example, be internally produced gas streams at a plant, like blast furnace top gas and BOF gas. In many places, at least some of the latter gases are not used but put to flaring. What is frequently hampering their greater use is the flame temperature required in heating applications. However, using oxyfuel instead of air-fuel would in many cases make it possible to even run solely a low calorific gas as fuel. Where these gases are being flared today, the resultant impact on the site's CO₂ emissions of using them in this way would be very positive and would replace other energy sources. A practical example of an increased use of a low grade fuel can be found in blast furnace hot stoves, where due to the oxygen-enrichment it leads to improved fuel economy and reduced CO₂ emissions.

As the examples and solutions discussed in this chapter all use oxygen, it is appropriate to comment on the CO₂ emissions relating to oxygen production. The production of 1 Nm³ of gaseous oxygen requires approximately 0.5 kWh of electricity. If this electricity is produced by hydro or nuclear power plants, it "carries" no CO₂. However, if produced using fossil fuel it would correspond to 0.5 kg CO₂ per Nm³ of oxygen. Thus, in the worst case scenario, oxyfuel combustion contributes (from oxygen production) 0.1 kg CO₂ per kWh. Turning that worst case scenario into practice, it is known that oxyfuel combustion (compared with air-fuel) would reduce the fuel consumption by an average of 40%, and the combined effect on CO₂ emissions would then be a reduction of approximately 35%.

9. Conclusions

The traditional use of oxyfuel in steel-making is in the electric arc furnace. Today sophisticated wall-mounted equipment is used combining the functions of oxygen and coal lancing, oxyfuel burner, and post-combustion. The level of oxygen use could reach above 50 Nm³/t, more than in the steel-making converter in integrated steel mills.

Mainly due to the strive to reduce CO₂ emissions the Full Oxygen Blast Furnace concept is now being tested. Here oxygen is completely replacing the air-blast. However, in a short-term perspective it seems advantageous to instead focus on the hot stoves, where low calorific fuel can be used to an increased extent, a typical benefit from oxyfuel.

Oxyfuel provides an overall thermal efficiency in the heating of 80%, air-fuel reaches 40-60%. With flameless oxyfuel, compared to air-fuel, the energy savings in a reheating furnace are at least 25%, but many times 50% or even more. It is possible to operate a reheat furnace with fuel consumption below 1 GJ per tonne. The corresponding reduction in CO₂ emissions is also 25-50%. Savings in terms of NO_x emissions are substantial. Flameless oxyfuel combustion has major advantages over conventional oxyfuel and, even more, over any kind

of air-fuel combustion. The improved temperature uniformity is a very important benefit, which also reduces the fuel consumption further.

With oxyfuel it is possible to increase the throughput rate by up to 50%. This can be used for increased production, less number of furnaces in operation, increased flexibility, etc. It is also of interest when ramping up production; two furnaces can cover the previous production of 2.5-3 furnaces, meaning possibility to post start-up of the third furnace and, additionally, resulting in decreased fuel consumption. Increased capacity can also be used to prolong soaking times. Thanks to the reduced time at elevated temperatures, oxyfuel leads to reduced scale losses, at many installations as high as 50%.

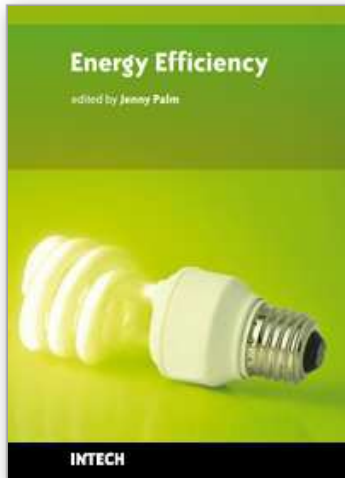
Using DFI Oxyfuel, where the flames heat directly onto the moving material, a very compact solution has been established. Installations show the production throughput can be increased by 30%, but it also provides other important benefits. This technology is particularly suitable for strip processing.

The experiences from converting furnaces into all oxyfuel operation show energy savings ranging from 20% to 70%, excluding savings in energy needed for bringing the fuel to the site. The use flameless oxyfuel in ladle and converter preheating is extremely advantageous. Now we also see that this innovative technology can be used at blast furnace hot stoves to improve energy and production efficiencies and reduce environmental impact.

There exist today a number of solutions and technologies which could substantially decrease CO₂ emissions without seriously altering current methods of operation and are therefore short-term viable solutions. Additionally, they would lead to improved fuel economics and reduced processing times. In heating and melting, oxyfuel combustion offers clear advantages over state-of-the-art air-fuel combustion, for example regenerative technology, in terms of energy use, maintenance costs and utilization of existing production facilities. If all the reheating and annealing furnaces would employ oxyfuel combustion, the CO₂ emissions from the world's steel industry would be reduced by 100 million tonnes per annum. Additionally, a small off-gas volume and a high concentration of CO₂ make it increasingly suitable for Carbon Capture and Sequestration.

Using oxyfuel instead of air-fuel combustion for all kinds of melting and heating operations opens up tremendous opportunities, as it leads to fuel savings, reduces the time required for the process and reduces emissions. Numerous results from installations have proven this.

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Energy Efficiency

Edited by Jenny Palm

ISBN 978-953-307-137-4

Hard cover, 180 pages

Publisher Sciyo

Published online 17, August, 2010

Published in print edition August, 2010

Global warming resulting from the use of fossil fuels is threatening the environment and energy efficiency is one of the most important ways to reduce this threat. Industry, transport and buildings are all high energy-using sectors in the world and even in the most technologically optimistic perspectives energy use is projected to increase in the next 50 years. How and when energy is used determines society's ability to create long-term sustainable energy systems. This is why this book, focusing on energy efficiency in these sectors and from different perspectives, is sharp and also important for keeping a well-founded discussion on the subject.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Joachim Von Schéele (2010). Oxyfuel Combustion in the Steel Industry: Energy Efficiency and Decrease of CO₂ Emissions, Energy Efficiency, Jenny Palm (Ed.), ISBN: 978-953-307-137-4, InTech, Available from: <http://www.intechopen.com/books/energy-efficiency/oxyfuel-combustion-in-the-steel-industry-energy-efficiency-and-decrease-of-co2-emissions>

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